ULTRASONIC IMAGING OF INTERNAL STRUCTURES OF A FIBER STEERED COMPOSITE PANEL

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INTRODUCTION

Fiber placement as a manufacturing method for composite parts has gained popularity in recent years. Fiber placement has been used not only in the manufacturing of military hardware such as the inlet duct of the joint strike fighter[1] and the landing gear pod fairing of the C-17 transport[2], but also in the manufacturing of lighter aircraft for civil aviation[3]. Fiber placement technology has a number of advantages over hand layup processes. It can be used to fabricate composite components with highly complex shapes in one automated, computer-controlled program. The savings in labor and low scrap rate combine to reduce the production costs by as much as 50%. The computer-controlled robotic operation also leads to a more consistent product.

In fiber placement, the tows are drawn under tension by a robotic head and simultaneously compacted and steered to the desired orientation and ply build-up and then cut. The control of fiber adds and cuts (the start and stop of tows) is controlled by computer via a CAD interface. The fiber placement machine lays down a number of tows in a course, many courses form a ply, and a number of plies make a laminate. In the manufacturing of composite components it is desirable to place the reinforcing fibers along the load path, and hence the interest in developing fiber steering capabilities. However, the complexity of the fiber architecture becomes greatly increased with fiber steering and the components will contain fiber adds and cuts between the courses.

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The most cited nondestructive inspection (NDI) task for the fiber placed composites is the evaluation of the gaps and overlaps of the towpregs between courses. Ideally these "gaps and laps" should be absent. The quality of a cured fiber placement panel may be evaluated with ultrasonic scans and imaging. Due to the small width of the towpregs, a focused high-frequency ultrasonic beam is usually required to image the structure of the fiber placed laminate. There are a number of challenges in imaging internal structures of composites ultrasonically. First, the structure is three-dimensional; the towpregs are not aligned in the thickness direction. Secondly, an echo reflected from an interior anomaly is always convolved with the disturbances to the waves due to the material above the anomaly. Thirdly, the limited bandwith of the ultrasonic pulse causes multiple images of a single reflecting interface. Despite such difficulties, ultrasound can still be used for the imaging of defects and fiber architectures in composites.[4] The recent work of French researchers[5] has added impetus to imaging internal structures using high frequency ultrasound.

With the presence of fiber steering, the gaps and laps are related to the numerous starts and stops of the towpregs. One must therefore judiciously choose the ultrasonic frequency, bandwith, and focusing conditions in order to obtain clear and informative images of the interior structures of a fiber placed panel with steering. In this work we use a moderately high frequency focused beam to generate a planar image of the panel in the form of a C-scan, thereby identifying locations with more severe gaps and laps. We then use a higher frequency, sharply focused beam to image the interior structures of the panel in the form of a B-scan.

DESCRIPTION OF FIBER STEERING PANEL

The fiber placed panel that was examined in this study is a 16-ply quasi-isotropic laminate. The lay-up sequence is $[(0/45/90/-45)_2]_S$. The nominal thickness of the towpreg is 10.4 mils. The thickness of the panel is 0.165". The fiber placement machine lays down courses of towpregs, with 12 towpregs per course. The width of each course is approximately 2", so the nominal width of a tow is 1/6".

The fiber-steered panel contains a 45-degree bend with an inner radius of 21" and an outer radius of 39". The 0-degree tows follow the curvature of the panel around the bend. The 90° tows are slightly divergent to maintain local orthogonality to the 0° tows. The 45° and -45° tows are curving in order to be at the correct angle relative to the local 0° and 90° tows. A sketch of the panel is shown in Figure 1.

By design the 45°, 90°, and -45° plies have overlaps and gaps between the courses. The fiber placement machine was programmed to start and stop the outer edge towpregs so that the maximum amount of overlap or gap is 50% of a towpreg width. There are numerous starts and stops of towpregs in these plies. These starts and stops create "convergence gaps" or areas where the plies above and below move in to fill a gap. The starts and stops for the 45° and 90° plies can be seen in Figure 2.

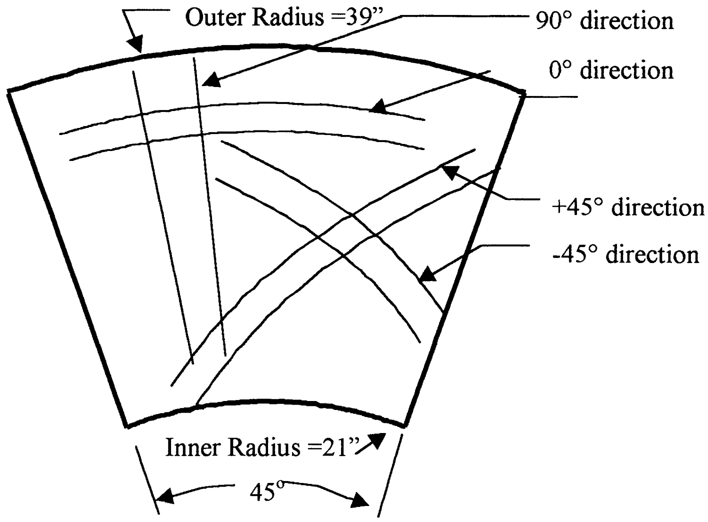


Figure 1 Sketch of Fiber Steering Panel and Towpreg Orientation.

ULTRASONIC C-SCANS MAPPING OUT DIRECTIONS OF COURSES

Ultrasonic C-scan images were obtained over portions of the fiber steered panel using a 15MHz, 0.5" diameter transducer with a 2" focal length. The focal point was placed on the back surface of the panel and a raster C-scan was made using the amplitude and time of flight of the back surface reflection. These results are shown in Figure 3. In these images, all fiber directions of the fiber steering panel were imaged. The 0-degree tows are nearly vertical in the figure and the 90-degree tows are nearly horizontal. The curvature of the ±45-degree plies was visible and the divergence of the 90-degree plies was also revealed. The dark streaks in the amplitude C-scan (Figure 3(a)) correspond to lower echo amplitude. They are probably caused by gaps and laps between courses of

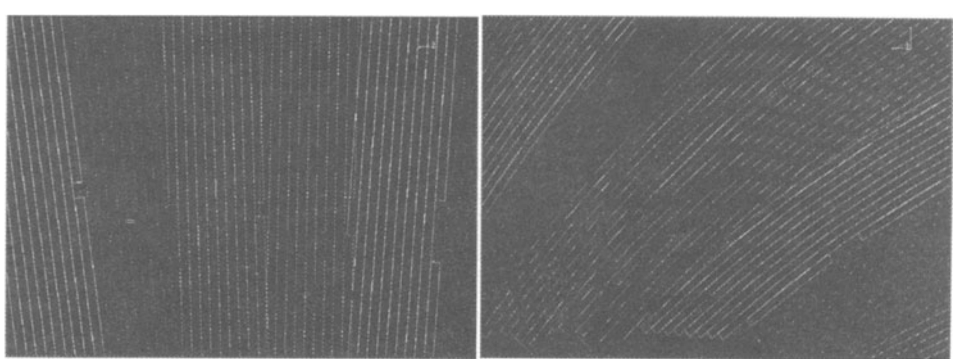
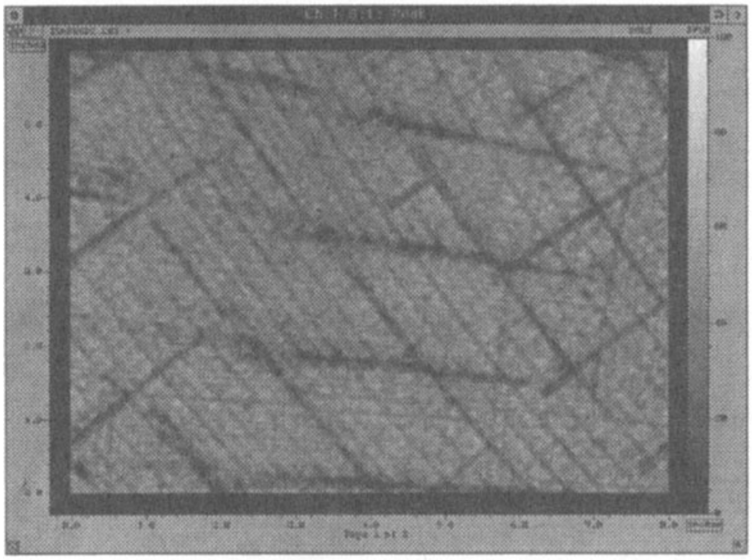
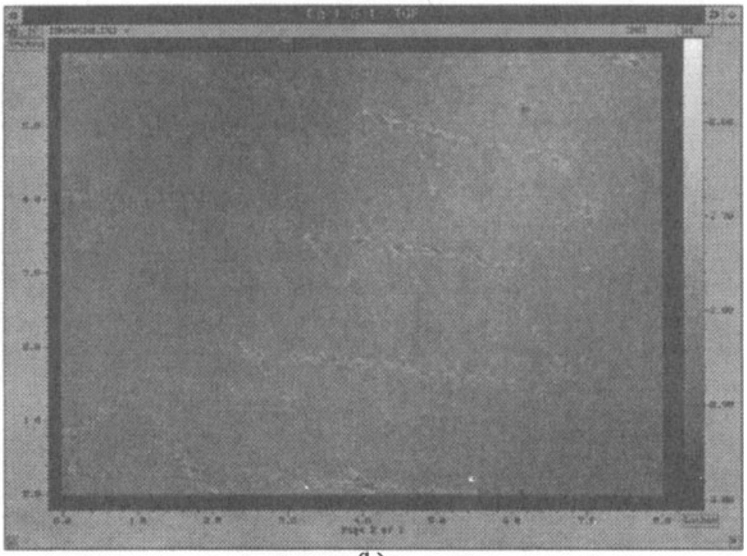


Figure 2 Starts and stops in a 90° ply (left) and a 45° ply (right). Notice the gaps and overlaps created by the starts and stops.

towpregs. Notice that the 0° tows have the least number of dark streaks, which is to be expected. Since the C-scan images were based on the back surface reflection, they represent an integrated effect over the entire thickness. Future comparisons between the C-scan images and micrographs of sectioned samples should prove instructive.



(a)



(b)

Figure 3(a) Amplitude C-scan of 8” x 6” portion of fiber steered panel.
Figure 3(b) Time of Flight C-scan of 8” x 6” portion of fiber steered panel.

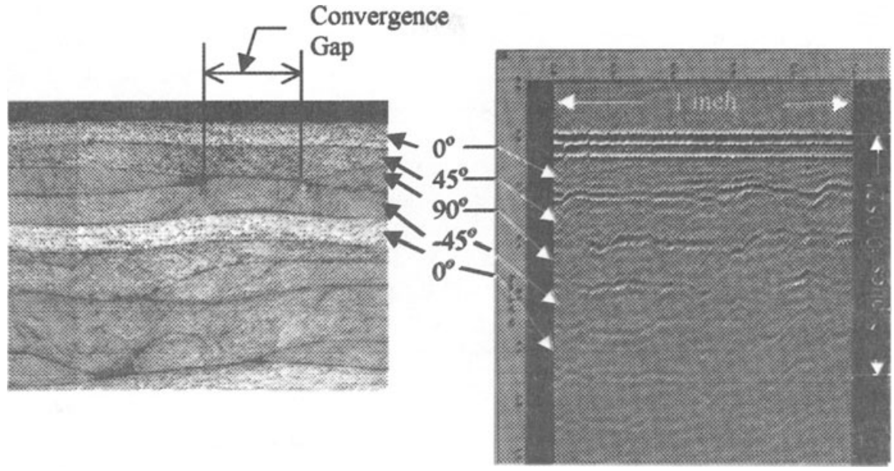


Figure 4 Micrograph (left) and B-scan image (right) showing the presence of a "convergence gap."

ULTRASONIC B-SCANS SHOWING INTERNAL STRUCTURES

The internal ply structures of the fiber placed graphite epoxy laminate containing fiber steering were imaged ultrasonically with a high frequency (50MHz center frequency) focused probe with resolution better than a single ply thickness. A "convergence gap" in the 90-degree ply was detected and imaged (Figure 4). The ultrasonic images were obtained by conducting a B-scan with the focal point placed approximately at the midplane of the panel.

The optical micrograph of the fiber placed panel, obtained destructively, was not taken at the location of the ultrasonic B-scan. However, a comparison of the micrograph and the UT image shows that they both contain a clearly defined convergence gap in the 90° ply (third ply from the top surface). The horizontal and vertical axes of the UT image in Figure 4 are both length but in very different scales. It can also be clearly observed that the ply interfaces below the convergence gap were increasingly distorted. This distortion was caused by the presence of the convergence gap. Unfortunately, this means that anomalies in the laminate would cast a shadow below it in B-scan images and that the part of the sample located in the shadow of a shallower defect could not be imaged faithfully.

IMAGING OF PLY INTERFACES IN HAND LAYUP PANEL

With the improved sensitivity and resolution achieved in the ultrasonic imaging of the fiber-steered composite, we revisited the ultrasonic reflectivity of ply interfaces in a quasi-isotropic hand lay-up laminate. The lay-up sequence for this laminate is

$[(0/45/-45/90)_2]_S$. With a high frequency (50 MHz center frequency) probe focused below the top surface of the laminate, B-scans revealed greater reflectivity at interfaces where the fiber direction changes from one ply to the next. In contrast, the reflections of interfaces not associated with a fiber direction change are weaker. This can be seen in Figure 5. Weaker reflections occur at interfaces 4, 8, and 12. These locations correspond to interfaces between two plies of 90°, 0° and 90° fiber directions respectively. As shown in the figure, it appears that we were able to resolve individual ply interfaces down to about the 12th ply for this sample. Therefore, the entirety of the 16-ply composite may be inspected by two scans, one from each surface. It is interesting to compare the ultrasonic reflectivity and the electrical conductivity of the ply interfaces[6]. In both cases it is the local fiber volume fraction and the random contacts between the fibers at the ply interfaces that affect the respective wave propagation and electrical conduction behaviors.

The ultrasonic B-scan image in Figure 5 shows that the quality of the panel (judged by the parallelness and flatness of the plies and the reflection strength of the internal surfaces) may be evaluated using B-scan imaging at high frequencies. A good quality panel would presumably have flat interfaces that are only weakly reflecting.

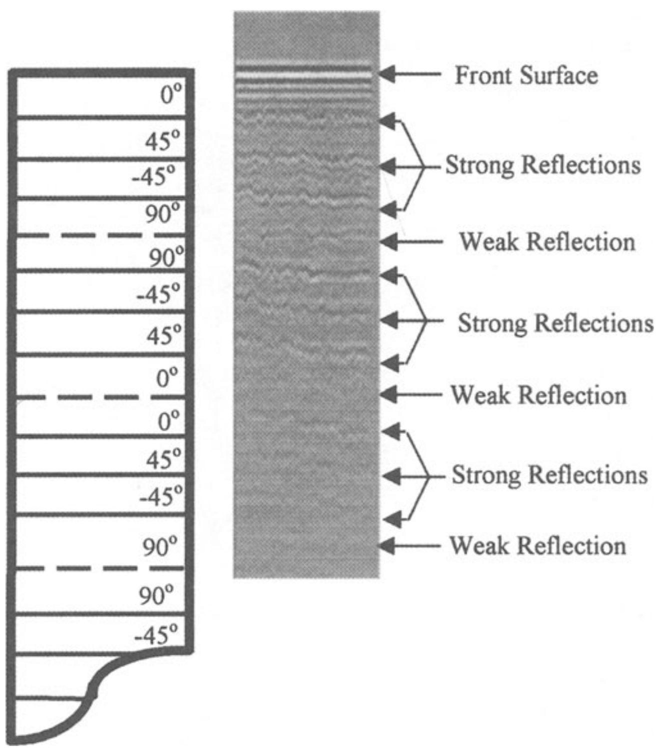


Figure 5 B-scan image of quasi-isotropic tape lay-up laminate.

CONCLUSION

This preliminary investigation of a fiber placed panel containing a 45° bend has demonstrated that ultrasonic C-scan and B-scan imaging can reveal a number of internal structures of the composite. Future work should include some destructive analysis by cutting the scanned specimen at selected locations in order to make direct comparisons between the ultrasonic images and the actual fiber placement results.

ACKNOWLEDGEMENT

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